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SURFACE RUNOFF SUPPLY ESTIMATES BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERNS

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SURFACE RUNOFF SUPPLY ESTIMATES BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERNS

By Leonard Schiff, hydraulic engineer, Division of Drainage and Water Control, Soil Conservation Service--Research

THE PROBLEM AND OBJECTIVES OF THE STUDY

The infiltration method of estimating runoff utilizes infiltration curves developed from hydrograph analysis and data obtained with infiltrometers. The basic theory of this method has been presented by R. E. Horton, L. K. Sherman, W. W. Horner, H. L. Cook, and others. Horner and Jens *(1)*[1] have utilized infiltration capacities and precipitation patterns for the development of surface runoff. More recently information has been developed on the transmission rate, (linear velocity of water), and percolation rate, (rate at which water passes a specific soil level), within the soil profile. Considerable data of this type are now being accumulated under the research program of the United States Department of Agriculture.

The objective of this paper is the development of a method of utilizing transmission rates, antecedent soil moisture, changes in soil moisture, and rainfall patterns for estimating surface runoff. The method presented involves the following concepts:

1. *Transmission rates of specific magnitudes may be applied to soils of reasonably similar hydrologic characteristics.*

2. *Transmission rates may be converted into corresponding infiltration rates.*

3. *An 'in place' supply of water to the soil surface may be estimated. This 'in place' supply may be translated into the hydrograph of stream flow for a given sub-basin. The hydrographs for the sub-basins may be combined for the entire basin. Estimates of the actual flow at any point must consider subsurface flow where such flow is appreciable.*

EXPERIMENTAL PROCEDURE

Rainfall, runoff, and soil moisture data were obtained from two watersheds of about 1.5 acres, for the period 1946 to 1948, inclusive. For this period both watersheds followed a rotation of wheat, meadow, and meadow. Such cover reasonably protected the soil surface against sealing. The soil on one of these watersheds is Muskingum silt loam, which is classified as well-drained. The soil on the other watershed is Keene silt loam, which is classified as slowly permeable.

Using infiltration curves to represent the supply of water to the soil and changes in soil-moisture content, transmission and percolation rates were determined for Muskingum silt loam and Keene silt loam. Methods and results of analyses were presented by Schiff and Dreibelbis *(2, 3)*.

Transmission and percolation rates were also obtained by testing a few hundred core samples of soil from Muskingum silt loam and Keene silt loam. These soil cores were 3 x 3 inches. Water was applied in drop form close to the surface of the soil, allowing the drops to fall at different points. Drops were applied rapidly enough to insure maximum rates of water movement through the soil cores. The time required for water to move through the soil cores and appear at the bottom was determined. Velocities or

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[1] Italic numbers in parentheses refer to Literature Cited, p. 18.

transmission rates were then computed. The application of water was continued and amounts of water applied to the surface of the cores and amounts passing through the cores were determined from time to time. The percolation rate was considered to be the rate of water application when the volume of percolate equaled the volume of water applied to the surface over a given period of time. This occurred when the soil was at or near saturation. The field soil-moisture content was also determined for each core. Methods and results of analyses were presented by Schiff and Dreibelbis (*4*).

Terms and symbols used are listed below:

P_g--*Accumulated ground rainfall*

i_g--*Intensity of ground rainfall.*

Infiltration--*The passage of water through the surface of the soil into the soil mass.*

f_p--*Infiltration capacity or potential infiltration rate, that is, the rate at which infiltration would take place at any instant were the supply to equal or exceed this capacity.*

Q_s--*Accumulated surface runoff.*

T_1Q_s *and* T_2Q_s--*Theoretical accumulated surface water supply to runoff, that is, the supply equal to* $i_g - f_p$ *without subsurface flow contributions. (*T_1 *and* T_2 *refer to two different methods.)*

S--*Pore space or storage space available in the soil at a given time.*

Transmission--*The movement of water downward through a given depth within the soil mass, that is, a linear velocity of water through a given depth of soil.*

t--*Transmission rate,* t_{ts} *is the transmission rate in the topsoil,* t_{ss} *is the transmission rate in the subsoil.*

Percolation--*The water passing a given level within the soil mass, that is, a depth of water over a given area passing a specific soil level in a specific period of time. It is equal to the area of pore space multiplied by the transmission rate through this pore space for a given period of time, St.*

g--*Percolation rate.*

STEPS IN ESTIMATING SURFACE RUNOFF

Steps in estimating surface runoff are outlined below and detailed later:

1. *Prepare a table showing the theoretical transmission rates required in soil at various soil-moisture contents to absorb various infiltration rates.*

2. *In this table place a line under the transmission rate of the topsoil, a line under the transmission rate of the subsoil, and other portions of the soil profile if necessary, for the particular soil studied.*

3. *Using this table prepare potential infiltration curves,* f_p, *for selected antecedent soil-moisture contents and changes in moisture contents.*

4. *These f_p curves may be applied to an anticipated storm, a particular storm, or to a specific storm pattern that may be expected in any locality. The difference between the ground intensity bargraph and the potential infiltration curve, $i_g - f_p$, is the 'in place' surface supply of water to runoff.*

5. *This 'in place' supoly of water may be translated into the surface runoff hydrograph of stream flow for a given sub-basin.*

6. *The surface runoff hydrographs for the sub-basins may be combined for the entire basin and when further combined with the subsurface flow hydrograph may be translated into stream flow.*

Steps 5 and 6 are not discussed herein. They involve the translation of $i_g - f_p$ into stream flow, such as through surface detention and channel storage computations.

To avoid numerous repetition of units in the following discussion, soil-moisture content is expressed in inches of water per inch of soil. Field capacity is nearly enough, 0.30 inch of water per inch of soil for the topsoil and subsoil of Muskingum silt loam and the topsoil of Keene silt loam and 0.36 inch for the subsoil of Keene silt loam. Saturation is nearly enough, 0.50 inch for the topsoil and subsoil of both Muskingum and Keene silt loam. The topsoil is the depth of soil from 0-7 inches and the subsoil is the depth of soil from 7-14 inches.

Step 1 - Studies *(2)*, *(3)*, *(4)* and by others, show that a considerable rate of ground rainfall establishes somewhat of a 'saturated front' that moves downward through soils of the type considered herein. The infiltration rate is a function of the transmission rate within the soil. *Table 1, page 4,* presents theoretical transmission rates required in soil at a given soil-moisture content to absorb various infiltration rates. For example, the transmission rate of 20 inches per hour, shown under the infiltration rate of 4.0 inches per hour and opposite a soil-moisture content of a 0.30 or 0.20 inch of available storage space per inch of soil was computed as follows: It requires 3 minutes to fill 0.20 inch of storage space with water at an infiltration rate of 4.0 inches. Since 0.20 represents the available storage space in an inch of soil, water must have moved 1 inch in 3 minutes and the transmission rate is 20 inches per hour. In other words, 0.20 inch of storage space multiplied by a transmission rate of 20 inches per hour equals an infiltration rate of 4.0 inches per hour. Other values in *table 1* were computed accordingly. If water did not move as a saturated front it would have moved more than 1 inch and the transmission rate would have been greater. This depends on the characteristics of the soil.

The percolation rate at a given level within the soil is equal to the infiltration rate if the soil is saturated above that level. Prior to saturation the percolation rate is equal to the infiltration rate minus the rate of exhaustion of pore space above the level considered.

Step 2 - The stepped solid line in *table 1* has been placed under 20 inches per hour, the maximum transmission rate generally found for Muskingum silt loam and Keene silt loam at Coshocton, Ohio *(2)*, *(3)*, and *(4)*. The dot and dash line represents Muskingum silt loam subsoil and has been placed under 6.7 inches per hour. The dotted line represents Keene silt loam subsoil and has been placed under 5.0 inches per hour. Subsoil values taken from references *(2)* and *(3)* were lower than those obtained by core sampling *(4)*. Values shown in reference *(2)* and *(3)* were obtained by using infiltration rates as the supply of water to the soil and frequently this supply was inadequate for maximum transmission rates in the subsoil. Values shown in reference *(4)* are higher for the subsoil and were obtained by the application of an adequate supply of water to soil

TABLE 1.--*Transmission rates necessary in soil at different moisture contents to absorb various infiltration rates*

Soil moisture per inch of soil	Available storage per inch of soil	Transmission rates necessary for infiltration rates in inches per hour of--																				
		0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.60	0.80	1.0	1.2	1.4	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0
IN	IN	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR	IN/HR
0.30	0.20	0.25	0.50	0.75	1.00	1.25	1.50	2.00	3.00	4.00	5.00	6.00	7.00	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0	35.0	40.0
.31	.19	.28	.53	.79	1.06	1.32	1.58	2.10	3.16	4.21	5.26	6.31	7.36	10.5	13.2	15.8	18.4	21.0	23.7	26.3	31.6	36.8	42.1
.32	.18	.28	.56	.83	1.12	1.39	1.67	2.22	3.33	4.44	5.55	6.66	7.77	11.1	13.9	16.7	19.4	22.2	25.0	27.8	33.4	38.9	44.4
.33	.17	.30	.59	.88	1.18	1.47	1.76	2.35	3.53	4.70	5.88	7.06	8.23	11.8	14.7	17.6	20.6	23.5	26.5	29.4	35.3	41.2	47.1
.34	.16	.32	.63	.94	1.25	1.57	1.87	2.50	3.75	5.00	6.25	7.50	8.75	12.5	15.6	18.8	21.8	25.0	28.1	31.2	37.5	43.8	50.0
.35	.15	.33	.67	1.00	1.33	1.67	2.00	2.67	4.00	5.33	6.67	8.00	9.33	13.3	16.7	20.0	23.3	27.7	30.0	33.3	40.0	46.7	53.3
.36	.14	.35	.72	1.07	1.43	1.79	2.15	2.87	4.29	5.72	7.14	8.56	9.99	14.3	17.9	21.4	25.0	28.6	32.1	35.7	42.8	50.0	57.2
.37	.13	.38	.77	1.15	1.54	1.92	2.31	3.08	4.61	6.15	7.69	9.21	10.7	15.4	19.2	23.1	26.9	30.8	34.6	38.4	46.2	53.8	61.5
.38	.12	.42	.83	1.25	1.67	2.08	2.50	3.33	5.00	6.66	8.33	10.0	11.7	16.7	20.8	25.0	29.2	33.3	37.5	41.6	50.0	58.3	66.7
.39	.11	.46	.91	1.36	1.82	2.27	2.73	3.64	5.46	7.28	9.09	10.9	12.7	18.2	22.7	27.3	31.8	36.4	40.9	45.5	54.5	63.6	72.7
.40	.10	.50	1.00	1.50	2.00	2.50	3.00	4.00	6.00	8.00	10.0	12.0	14.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	60.0	69.8	80.0
.41	.09	.56	1.11	1.67	2.22	2.78	3.33	4.45	6.67	8.88	11.1	13.3	15.6	22.2	27.8	33.4	38.9	44.5	50.0	55.6	66.7	77.8	88.9
.42	.08	.63	1.25	1.88	2.50	3.13	3.75	5.00	7.50	10.00	12.5	15.0	17.5	25.0	31.3	37.5	43.8	50.0	56.3	62.5	75.1	87.5	100.0
.43	.07	.71	1.43	2.14	2.86	3.57	4.28	5.72	8.57	11.4	14.3	17.2	20.0	28.6	35.7	42.8	50.0	57.2	64.3	71.4	85.7	100.0	114.0
.44	.06	.83	1.67	2.50	3.34	4.17	5.00	6.67	10.0	13.3	16.7	20.0	23.4	33.4	41.7	50.0	58.3	66.7	75.0	83.3	100.0	117.0	133.0
.45	.05	1.00	2.00	3.00	4.00	5.00	6.00	8.00	12.0	16.0	20.0	24.0	28.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	120.0	140.0	160.0
.46	.04	1.25	2.50	3.75	5.00	6.25	7.50	10.0	15.0	20.0	25.0	30.0	35.0	50.0	62.5	75.0	87.5	100.0	112.0	125.0	150.0	175.0	200.0
.47	.03	1.67	3.33	5.00	6.67	8.33	10.0	13.4	20.0	26.7	33.3	39.9	46.6	66.7	83.3	100.0	117.0	133.0	150.0	167.0	200.0	233.0	267.0
.48	.02	2.50	5.00	7.50	10.0	12.5	15.0	20.0	30.0	40.0	50.0	60.0	70.0	100.0	125.0	150.0	175.0	200.0	225.0	250.0	300.0	350.0	400.0
.49	.01	5.0	10.0	15.0	20.0	25.0	30.0	40.0	60.0	80.0	100.0	120.0	140.0	200.0	250.0	300.0	350.0	400.0	450.0	500.0	600.0	700.0	800.0
.495	.005	10.0	20.0	30.0	40.0	50.0	60.0																
.497	.003	16.7	33.3	50.0	66.6	83.3	100.0																
.498	.002	25.0	50.0																				
.499	.001	50.0																					

TOPSOIL, CULTIVATED CROPS ON MUSKINGUM AND KEENE SILT LOAM

SUBSOIL, CULTIVATED CROPS ON MUSKINGUM SILT LOAM

SUBSOIL, CULTIVATED CROPS ON KEENE SILT LOAM

cores. Obviously, the ability to correctly locate the stepped lines will determine the accuracy of relationships between soil moisture and infiltration rates. Differences in transmission rates do not appear great between the subsoils of Muskingum silt loam and Keene silt loam. However, the differences that do exist as well as the greater swelling of colloids in the subsoil of Keene silt loam, seem to cause considerable differences in hydrologic performance. This is evidenced by the higher moisture content of Keene silt loam antecedent to a storm, a major reason for greater runoff from Keene silt loam.

Step 3 - For Muskingum silt loam and Keene silt loam the water movement within the soil profile affecting the supply of water available for surface runoff takes place within the topsoil and the subsoil *(2), (3)*. When the soil is below field capacity and the supply of water is sufficient for infiltration to occur near capacity rates, water moves rapidly downward until it reaches the subsoil. Under such conditions when water reaches the subsoil the soil-moisture content of the topsoil will be about 0.46. When the topsoil is above field capacity water will move into the subsoil regardless of an approaching wet front. However, for most practical problems of surface runoff it may be assumed that water will enter the subsoil when infiltration exists near capacity rates and the soil-moisture content of the topsoil is equal to or greater than 0.46. In view of these considerations the soil-moisture contents of the topsoil and subsoil overlap at 0.46 on the horizontal scale in *figure 1, page 6*. When the soil-moisture content of the topsoil exceeds 0.46 the low transmission rates of the subsoil become the controlling factor and surface runoff becomes significant. Since one unit on the horizontal scale represents an increase in moisture content of 0.01 inch of water per inch of soil or 0.07 inch gain in the topsoil, two units are necessary for both the topsoil and subsoil to gain 0.01 inch of water per inch of soil or 0.14 inch gain in both the topsoil and subsoil. The scale was adjusted accordingly in the overlapping section. For this overlapping section the division of the total gain would be more accurate if based on the ratio of the storage space depletion rate of the topsoil to the subsoil. Such refinements are unnecessary for most practical solutions.

Table 1, page 4, was used to prepare the potential infiltration rate curves for various antecedent soil-moisture contents shown in *figure 1*. Plotting potential infiltration rates against soil-moisture results in straight lines of different slope, one for the topsoil, one while the remaining storage space is being exhausted in the topsoil as water moves through the subsoil, and one for the subsoil after the topsoil is saturated. However, in *figure 1* the potential infiltration rates for different soil-moisture contents were plotted as smooth curves, using the straight lines as guides.

As the soil-moisture content increases, the effective cross-sectional area through which water flows downward decreases, although transmission rates or velocities may remain approximately uniform and fairly high. Diminishing effective areas of cross section multiplied by the fairly constant velocity of flow result in diminishing rates of flow through the soil and consequently diminishing infiltration rates. After water begins to move slowly into a subsoil of lower transmission rates, the remaining storage space fills in the topsoil and the topsoil approaches saturation. The lower rates of exhaustion of this remaining, and generally small volume of storage space in the topsoil, and lower transmission rates in the subsoil usually are reflected by the section of greatest curvature in the infiltration capacity-rate curve when plotted against time. Values for this section were obtained from the subsoil steps in *table 1*. The infiltration curve, after the topsoil is saturated, is mainly a function of water-movement rates in the subsoil. The infiltration rate is further reduced as storage space is exhausted in the subsoil and probably approaches a minimum as the swelling of colloids becomes complete.

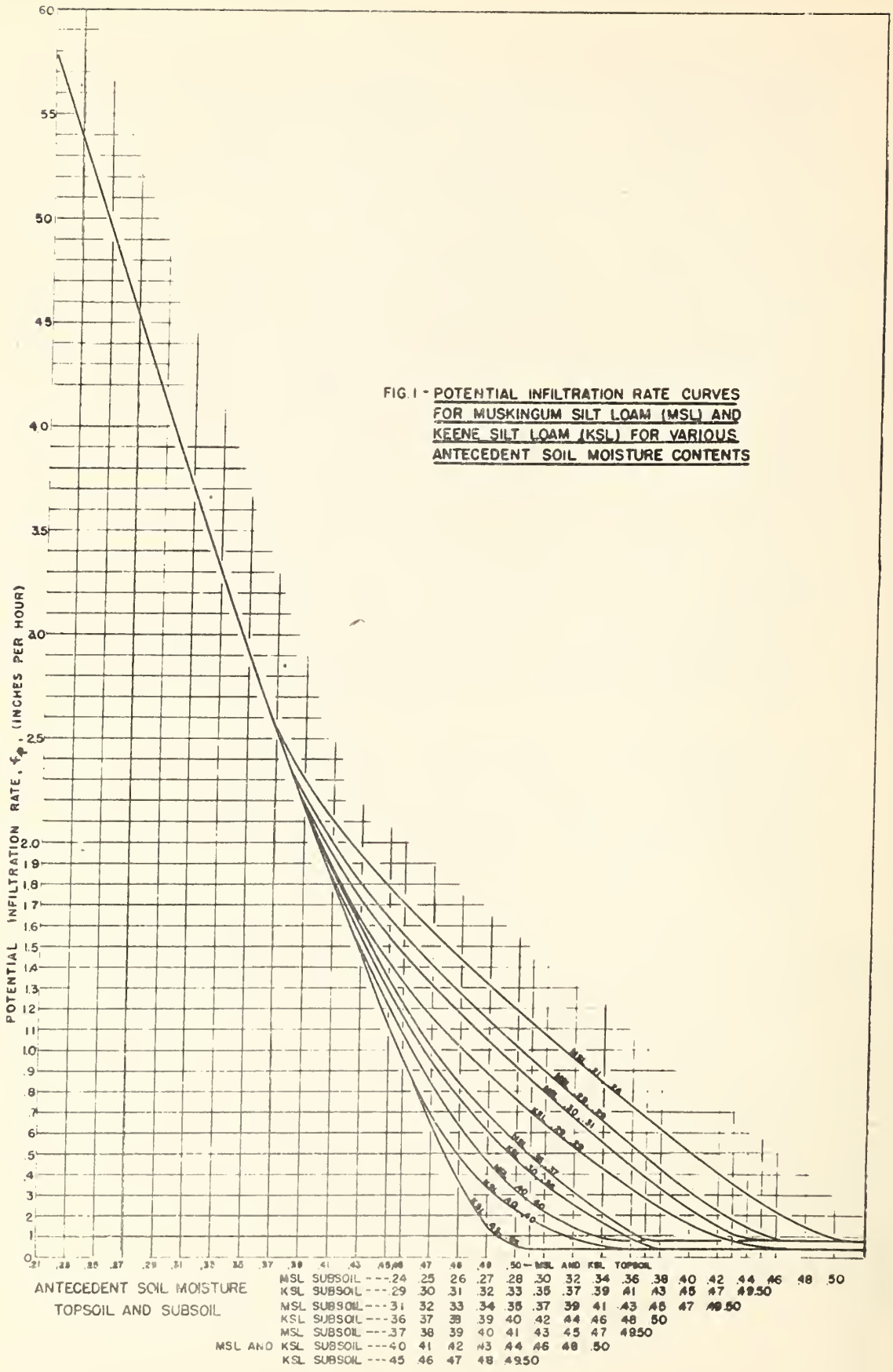
POTENTIAL INFILTRATION RATE, f_p, (INCHES PER HOUR)
ANTECEDENT SOIL MOISTURE
TOPSOIL AND SUBSOIL
MSL AND KSL TOPSOIL
MSL SUBSOIL ---24 25 26 27 28 30 32 34 36 38 40 42 44 46 48 50
KSL SUBSOIL ---29 30 31 32 33 35 37 39 41 43 45 47 49 50
MSL SUBSOIL ---31 32 33 34 35 37 39 41 43 45 47 49 50
KSL SUBSOIL ---36 37 38 39 40 42 44 46 48 50
MSL SUBSOIL ---37 38 39 40 41 43 45 47 49 50
MSL AND KSL SUBSOIL ---40 41 42 43 44 46 48 50
KSL SUBSOIL ---45 46 47 48 49 50

FIG. 1 - POTENTIAL INFILTRATION RATE CURVES FOR MUSKINGUM SILT LOAM (MSL) AND KEENE SILT LOAM (KSL) FOR VARIOUS ANTECEDENT SOIL MOISTURE CONTENTS

Sections making up the guide lines, from which the potential infiltration rate curves are drawn, would not be straight lines if transmission rates varied with progressive changes in soil moisture. However, transmission rates could be constant for a given horizon in the soil profile and storage space exhausted in such a fashion as to result in the curvature of various sections of the infiltration rate curve.

The curves shown in *figure 1, page 6*, were prepared for the soils at field capacity, 0.40, 0.45, and for combinations representing antecedent moisture conditions existing for the storms of June 16, 1946, and April 14, 1948. Such combinations are marked on each curve. For example the top curve is marked MSL .21, .24, which represents Muskingum silt loam at a soil-moisture content of 0.21 for the topsoil and 0.24 for the subsoil. This was the soil-moisture condition for the storm of June 16, 1946, on watershed 109. Numerous curves may be prepared in advance covering a number of likely soil-moisture conditions.

Step 4 - This step determines the supply of water to the soil surface using the potential infiltration rate curves shown in *figure 1* and the rainfall pattern. This supply of water will be equal to surface runoff if depression storage is negligible. Information from the previous steps may be developed prior to storms to which it is to be applied. Two methods have been developed to apply this information. The first method, T_1, is more rapid but not as accurate as the second method, T_2. Method T_1 assumes that all of the ground rainfall enters the soil, is uniformly distributed in the topsoil until the moisture content of the topsoil is 0.46 inch, is then equally divided between the topsoil and subsoil until the topsoil is saturated, and is then uniformly distributed in the subsoil. When the subsoil becomes saturated the minimum infiltration rate occurs. Assuming that all of the ground rainfall enters the soil, and omitting any correction for surface runoff, obviously assumes that more water enters the soil than is actually the case. However, this is somewhat compensated for by assuming uniform distribution of water in the subsoil after the topsoil is saturated. Actually, water moves slowly through the subsoil, and the upper portion of the subsoil is wetter than the lower portion for a considerable length of time.

Method T_1 is illustrated in *figure 2, page 8*, for the storm of June 16, 1946, on watershed 123, Keene silt loam, slowly permeable. Plot the accumulated ground rainfall, P_g, and the intensity of ground rainfall or intensity bargraph, i_g. The intensities of ground rainfall may be placed along the P_g curve corresponding to the slopes of the elements of the P_g curve, eliminating the need for the intensity bargraph. Next, the soil-moisture ordinates for the topsoil and subsoil are established. The antecedent soil-moisture content for the storm of June 16 was 0.29 for both the topsoil and subsoil. The value of 0.29 for the topsoil is placed opposite the ground rainfall of 0.00 inch on the vertical scale. For each 0.07 inch of ground rainfall the soil-moisture content of each inch of topsoil is increased by 0.01 until the value of 0.46 is reached, in this case opposite 1.19 inches of ground rainfall. The antecedent value of 0.29 for the subsoil is also placed opposite 1.19 inches, since at this point water begins to enter the subsoil. For each additional 0.14 inch of ground rainfall, the soil-moisture content of each inch of topsoil is increased by 0.01 until the topsoil is saturated, in this case opposite 1.75 inches of ground rainfall. After this time, for each additional 0.07 inch of ground rainfall, the soil-moisture content of each inch of subsoil is increased by 0.01 until the subsoil is saturated and the minimum infiltration rate established.

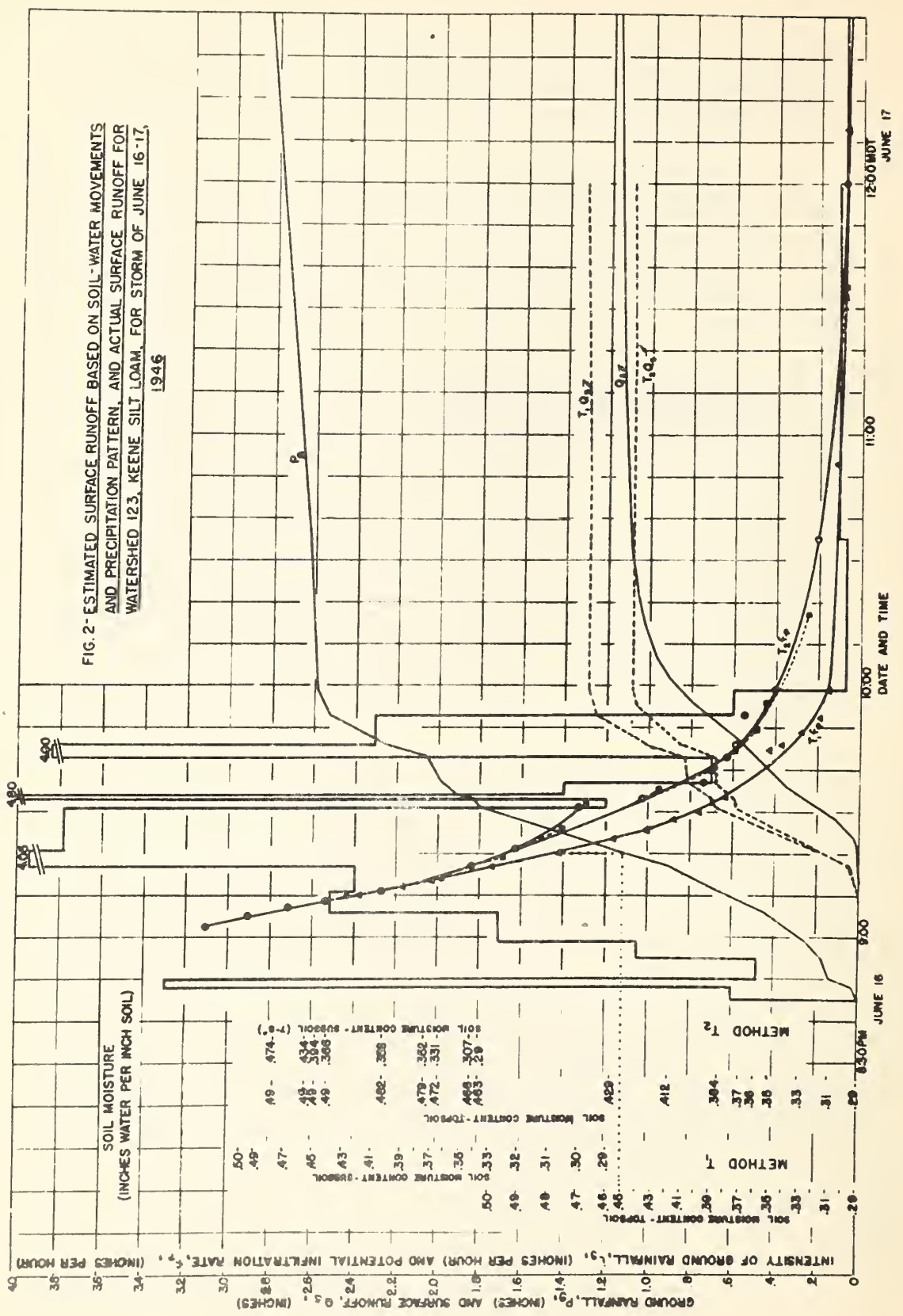

FIG. 2- ESTIMATED SURFACE RUNOFF BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERN, AND ACTUAL SURFACE RUNOFF FOR WATERSHED 123, KEENE SILT LOAM, FOR STORM OF JUNE 16-17, 1946

Plot potential infiltration rates on *figure 2, page 8*, obtained from curve KSL, .29, .29 in *figure 1, page 6*, corresponding to the ordinate of soil-moisture values established on *figure 2* and the accumulated ground rainfall, P_g. For example, for a soil-moisture content of 0.35 for the topsoil, curve KSL .29, .29 of *figure 1* shows a potential infiltration rate, f_p, of 2.9 inches per hour, shown as $T_1 f_p$ for method T_1 on *figure 2*. The value 2.9 is plotted above the intersection of the soil-moisture ordinate of 0.35 and the P_g curve. Similarly, plot sufficient other f_p points corresponding to other values of soil-moisture content to establish the curve $T_1 f_p$.

Intensities of ground rainfall, i_g, in excess of the $T_1 f_p$ curve, yield water-supply increments available for surface runoff. For example, from 9:17 p. m. to 9:21 p. m. i_g is 4.05 inches per hour and the average $T_1 f_p$ for this period of time is 1.54 inches per hour, a difference of 2.51 inches per hour. In this period of 4 minutes, a rate of 2.51 inches per hour is equal to 0.167 inch of water supply. Starting where the f_p curve first intersects the i_g bargraph compute each increment of water supply and accumulate the increments to establish $T_1 Q_s$, the theoretical accumulated water supply. If there is little depression storage $T_1 Q_s$ may be considered surface runoff.

At midnight of June 16, $T_1 Q_s$ is 1.32 inches as compared to 1.15 inches of actual surface runoff, Q_s. It is believed that some of this difference is due to the assumption that all of the ground rainfall entered the soil. Other differences are interesting. For example, since the $T_1 Q_s$ curve represents the total available water supply on the watershed at a given time for a given increment of rainfall it starts earlier and steeper than the Q_s curve. Initial runoff shown by a runoff-measuring flume usually comes from the area in the immediate vicinity above the flume. Obviously, the lag prevails throughout the runoff period as does the ironing out of the increments of water supply. These differences reflect the influence of the physical factors of the surface of the watershed upon the movement of the water supply to the measuring flume, where it is measured as surface runoff.

Method T_2 is also illustrated in *figure 2* for the storm of June 16, 1946, on watershed 123. This method is similar to method T_1, except that it accounts for the water entering the soil by subtracting the total increments of estimated surface runoff at any given time from the accumulated ground rainfall up to the same time. Also, the distribution of water within the topsoil and subsoil is made more strictly in accordance with soil-water movements. *Table 2, page 10*, shows how the accumulated surface runoff curve, $T_2 Q_s$ of *figure 2*, was obtained. A few f_p points are determined to locate and shape the f_p curve, shown as $T_2 f_p$ for method T_2, prior to its intersection with the intensity bargraph. *Column 1* of *table 2* shows such points to be taken at 9:02½, 9:05, 9:07, and 9:08½ p. m. when, between each of these times, increments of ground rainfall were 0.07 inch, *column 2*. For each of these time entries the gain in soil-moisture content of the topsoil is shown in *columns 10 and 11*. Values of f_p corresponding to these soil-moisture contents were obtained from *figure 1* and are 3.11, 2.91, 2.72, and 2.54 inches per hour as shown in *column 14*. A curve, through these points, was extended until it intersected the intensity bargraph at 9:08½ p. m. This curve was continued through the intensity bargraph section whose value is 2.54 inches per hour. For the period 9:08½ to 9:11 p. m. the difference between the i_g value of 2.54, *column 3*, and the trial average f_p value of 2.44, *column 4*, is 0.10 inch per hour, *column 5*. This difference, for the time interval of 2½ minutes, *column 6*, is equivalent to a trial increment of surface runoff of 0.004 inch, *column 7*. *Column 8* is the final $\Sigma\Delta Q_s$ of the previous line, *column 18*, plus the trial ΔQ_s of *column 7* for the interval being considered. Subtracting the trial ΔQ_s of 0.004 inch plus the final $\Sigma\Delta Q_s$, *column 18*

TABLE 2.--*Estimated surface runoff for watershed 123 for storm of June 16-17, 1946, using method* T_2

Time	P_g	i_g	Trial average f_p	Trial i_g - av. f_p	Time interval	Trial ΔQ_s	Final $\Sigma\Delta Q_s$ + trial ΔQ_s	$P_g - \Sigma\Delta Q_s$ + trial ΔQ_s	Soil-moisture content: Topsoil: Gain per inch	Topsoil: After gain	Subsoil: Gain 7-8"	Subsoil: After gain	Final f_p	Final average f_p	Final i_g - av. f_p	Final $\Sigma\Delta Q_s$	Final ΔQ_s	Final $P_g - \Sigma\Delta Q_s$
	In	*In/hr*	*In/hr*	*In/hr*	*Min.*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*In/hr*	*In/hr*	*In/hr*	*Inches*	*Inches*	*Inches*
Col. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
From[1] Fig. 2	Fig. 2	Fig. 2	Fig. 2	(3) - (4)	(1)	(6) x (5) / 60 min.	(7) + (18)	(2) - (8)	/2/	(10) + (11)	/2/	[3] (12) + (13)	Fig. 1	Fig. 2	(3) - (15)	(6) x (16) / 60 min.	[3] (17) + (18)	(2) - (18)
p.m.																		
9:02½	0.35	1.72	-	-	-	0	0	0.35	0.05	0.34	0	0.29	3.11	-	-	0	0	0.35
9:05	.42	1.72	-	-	2.5	0	0	.42	.01	.35	0	.29	2.91	-	-	0	0	.42
9:07	.49	2.54	-	-	2	0	0	.49	.01	.36	0	.29	2.72	-	-	0	0	.49
9:08½	.56	2.54	-	-	1.5	0	0	.56	.01	.37	0	.29	2.54	-	-	0	0	.56
9:11	.66	2.54	2.44	0.10	2.5	.004	.004	.656	.014	.384	0	.29	2.27	2.40	0.14	.006	.006	.654
9:17	.90	2.40	1.98	.42	6	.042	.048	.852	.028	.412	0	.29	1.84	2.05	.35	.035	.041	.859
9:21	1.17	4.05	1.69	2.36	4	.157	.198	.972	.017	.429	0	.29	1.63	1.73	2.32	.155	.196	.974
9:31	1.80	3.78	1.41	2.37	10	.395	.591	1.209	.034	.463	0	.29	1.33	1.44	2.34	.39	.586	1.214
9:33	1.84	1.20	1.30	0.00	2	.000	.586	1.254	.003	.466	.017	.307	1.03	1.07	.13	.004	.59	1.25
9:37	1.99	2.25	.95	1.30	4	.087	.677	1.313	.006	.472	.024	.331	.74	.90	1.35	.09	.68	1.31
9:43	2.06	.70	.70	0.00	6	.000	.68	1.38	.007	.479	.021	.352	.63	.72	0.00	.000	.68	1.38
9:46	2.26	4.00	.59	3.41	3	.171	.851	1.409	.003	.482	.006	.358	.59	.61	3.39	.17	.85	1.41
9:53	2.53	2.31	.49	1.82	7	.217	1.067	1.463	.008	.49	.008	.366	.55	.51	1.80	.21	1.06	1.47
9:59	2.58	.60	.45	.15	6	.015	1.075	1.505	.000	.49	.028	.394	.40	.43	.17	.017	1.077	1.503
10:35	2.63	.07	.25	.000	36	.000	1.077	1.553	.000	.49	.04	.434	.21	.28	.000	.000	1.077	1.503
12:00M.	2.78	.11	.08	.03	50	.025	1.102	1.678	.000	.49	.04	.474	.08	.09	.02	.013	1.09	1.69

[1] Entries obtained from figures and column numbers.

/2/ Gain per inch based on pore space depletion, see discussion of method T_2.

[3] (11), (13), or (18) obtained from column (11), (13), or (18) opposite previous time entry.

(in this case 0.000), from a P_g of 0.66 yields 0.656 inch as the total soil-moisture gain up to that time, *column 9*. This entry of 0.656 is 0.096 inch greater than the final P_g minus $\Sigma\Delta Q_s$ of 0.56, *column 19*, previous line. The value 0.096 for the entire topsoil represents a gain of about 0.014 inch of water per inch of topsoil, *column 10*. This gain of 0.014 when added to the previous entry of 0.37 inch in *column 11* is the total soil-moisture content of 0.384. The zero in *column 12* indicates no moisture gain in the subsoil, 7-8 inches. Consequently, the total soil-moisture content of the subsoil remains the same, 0.29, *column 13*. The f_p value obtained from *figure 1, page 6*, for a soil-moisture content of 0.384 (*column 11*) is 2.27 inches per hour, *column 14*, and is considered a final position point through which the f_p curve passes. The final average f_p for the interval 9:08½ to 9:11 p. m. is the 2.40 of *column 15*, rather than the trial value of 2.44 of *column 4*. The final i_g minus the average f_p is the 0.14 of *column 16* rather than the 0.10 of *column 5*. The final ΔQ_s is the 0.006 of *column 17* rather than the 0.004 of *column 7*. The 0.006 of *column 17* is the final $\Sigma\Delta Q_s$, which when subtracted from the P_g of *column 2* is the 0.654 of *column 19*. This procedure was continued step by step for the other intervals of the intensity bargraph. For greater accuracy, a long interval of constant intensity may be divided into parts.

To illustrate the method when water has reached the subsoil and is depleting storage space in both the topsoil and subsoil, consider the interval of intensity from 9:31 to 9:33 p. m. The value of 1.254 shown in *column 9* is 0.04 greater than the value of 1.214, previous line, *column 19*. The 0.04 was proportioned between the topsoil and subsoil on the basis of their storage space depletion rates *(2)*. This resulted in 0.023 inch gain for the topsoil and 0.017 for the subsoil. The topsoil gain was considered to be 0.003 inch per inch as shown in *column 10* and 0.017 inch for the 7-8-inch depth of the subsoil as shown in *column 12*. Similarly the remainder of *table 2, page 10*, was completed and *column 18* was plotted on *figure 2, page 8*, as T_2Q_s. Total surface runoff, T_2Q_s, is 1.09 as compared to an actual surface runoff, Q_s, of 1.15 inches. If the T_2Q_s curve were absolutely correct the area between the T_2Q_s and Q_s curves, after their intersection, could be considered the amount of subsurface flow return.

Where the slope of the T_2Q_s curve is constant for a period of time at least equal to the 'time of concentration' of the watershed it may be considered an approximation of the rate of runoff. For example, the rate of runoff based on the slope of T_2Q_s over the period of time from 9:17 to 9:31 p. m. is 2.31 compared to an actual rate of 1.91 inches per hour occurring at 9:32 p. m. Rates of runoff may be estimated for slopes for periods less than the time of concentration.

Figure 3, page 12, shows the two methods for the same storm on watershed 109, Muskingum silt loam, well-drained. Less runoff on watershed 109 than on watershed 123 is due more to its lower antecedent soil-moisture condition prior to a storm than to its higher transmission rates. There are more soil particles of colloidal dimension in Keene silt loam and greater swelling probably accounts largely for the poorer drainage during and between storms on watershed 123.

Figure 4, page 13, shows T_1Q_s for the storm of April 14, 1948, on watersheds 123 and 109. Of particular note is the shape of f_p, which shows sudden drops with sudden increases in rainfall intensity and soil-moisture content. There is close agreement between theoretical and actual runoff. If there are long periods in a storm during which no rain falls there will be a decrease in the soil-moisture content, which may be estimated from soil-moisture depletion rates *(3)*. Storage space and the potential infiltration rate are thus increased. When rain begins to fall again the infiltration rate will be based on the actual storage space at the time and will show the recovery that seems somewhat difficult to establish.

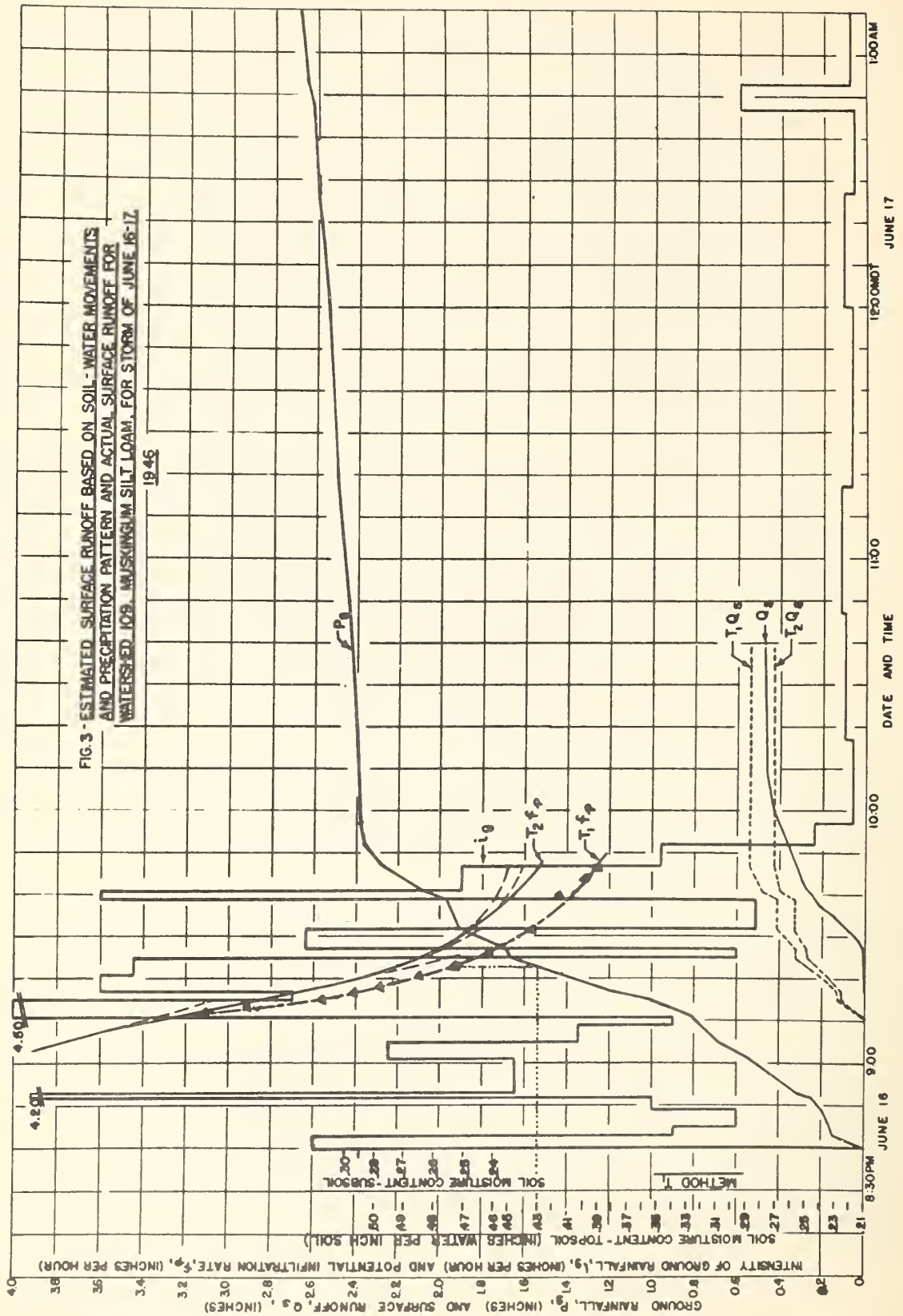

FIG. 3 - ESTIMATED SURFACE RUNOFF BASED ON SOIL - WATER MOVEMENTS AND PRECIPITATION PATTERN AND ACTUAL SURFACE RUNOFF FOR WATERSHED 109, MUSKINGUM SILT LOAM, FOR STORM OF JUNE 16-17, 1946

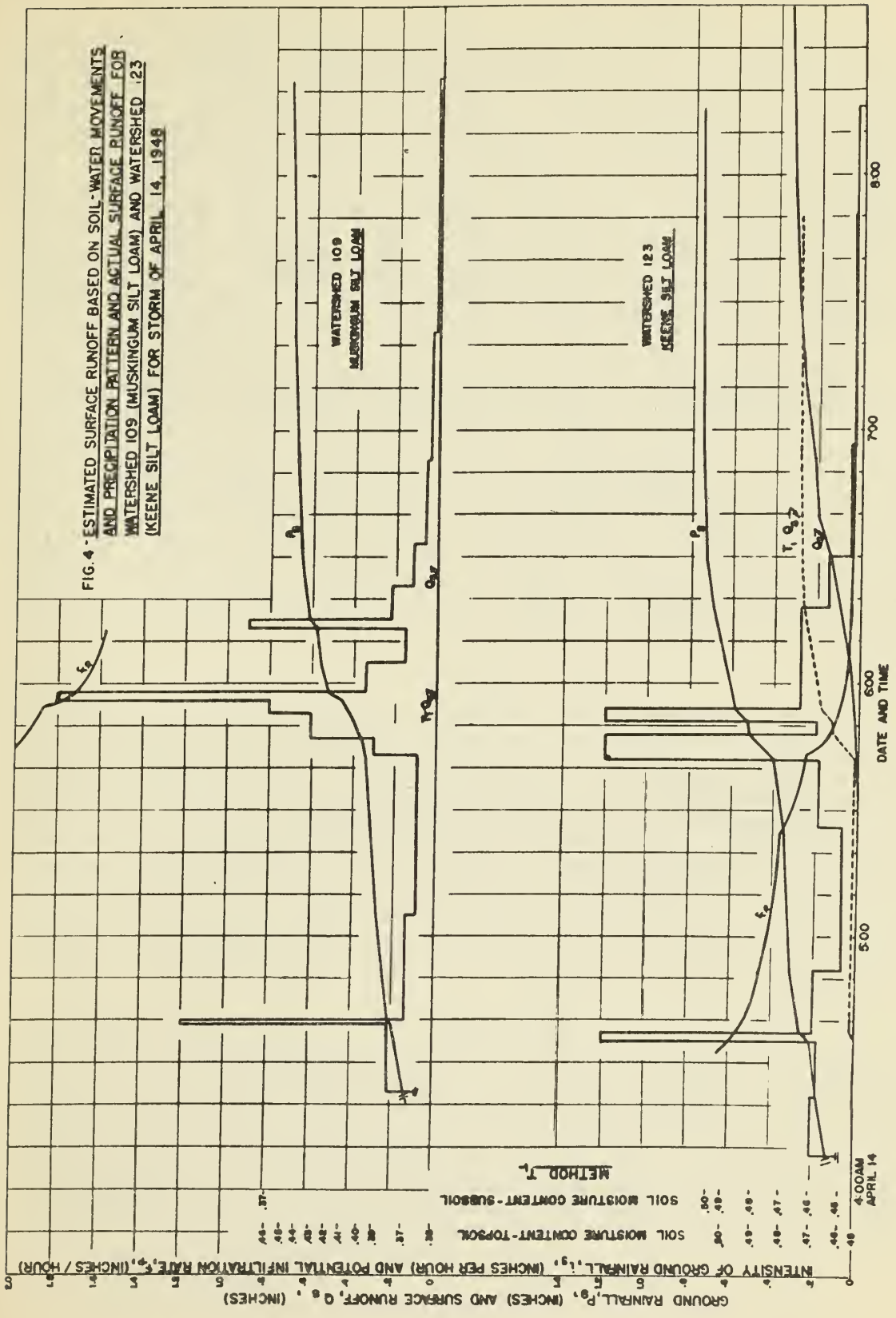

FIG. 4 - ESTIMATED SURFACE RUNOFF BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERN AND ACTUAL SURFACE RUNOFF FOR WATERSHED 109 (MUSKINGUM SILT LOAM) AND WATERSHED 123 (KEENE SILT LOAM) FOR STORM OF APRIL 14, 1948

These methods may be applied to an anticipated storm, a particular storm or to a specific storm pattern. Potential infiltration curves may be prepared for various antecedent soil-moisture conditions and superimposed over various storm classes and patterns that might occur in a given locality. Five classes and six patterns have been developed for rains at Coshocton, Schiff *(5)*. The classes refer to various combinations of rainfall intensities of certain magnitudes and the patterns refer to the sequence of these intensities. Seasonal occurrences of these classes of storms in the province represented by Coshocton, are generally as follows: Class I, winter; class II, winter and early spring; class III, fall; class IV, late spring and summer; and class V, summer. The advanced and delayed patterns, highest intensities occurring near the beginning and end of storms, respectively, are used for illustration herein, as all other patterns fall between these. Whenever possible, antecedent soil-moisture conditions should be obtained by actual field determinations of the soil-moisture content rather than by estimates based on rainfall. Better relationships between rainfall and soil-moisture content might be established in the light of information on rainfall, percolation, and evapo-transpiration.

Figures 5 and 6, pages 15 and 16, show f_p curves obtained from *figure 1, page 6*, for various antecedent soil-moisture conditions, applied to advanced and delayed patterns of five classes of rainfall. Resulting runoff based on method T_1 is also shown in *figures 5 and 6*. For storm classes I, II, and III, an antecedent soil-moisture content of 0.40 was used. For storm class IV and V field capacity was used, with the exception of one soil-moisture condition taken at 0.21, 0.24 for Muskingum silt loam and 0.29, 0.29 for Keene silt loam, soil-moisture contents actually existing prior to the storm of June 16, 1946. A delayed pattern storm produces more runoff than an advanced pattern storm as the high intensities fall on soil whose moisture content has increased under the influence of the lower intensities at the beginning of the storm. Greater runoff occurs on Keene silt loam for reasons given previously. There is close agreement between the actual runoff for the storm of June 16, 1946, a class IV, Pattern A type storm, and theoretical runoff for such a type storm and similar soil-moisture content on watersheds 123 and 109, as shown in *figure 6*.

SUMMARY

This paper attempts to set up a fundamental attack that involves two important objectives. The first is concerned with estimates of surface supplies to runoff and is dealt with directly. Potential infiltration curves can be used to estimate surface supplies to runoff by superimposing them over storm patterns of various types that have occurred or are expected to occur. Infiltration curves based on soil-water movements should give a better understanding of the ranges and recoveries of such curves for different soils and land use. The second objective, possibly of even greater ultimate importance, although not emphasized in this particular paper, is an approach which will lead to knowledge of the influence of soil properties and land use upon the hydrologic performance of watersheds. Soil-water movements represent the supply of water to the soil profile and are important considerations in land use and subsurface-type flows. The actual rate of flow at any given point in the drainage basin is a function of subsurface flow contributions as well as the action of the physical characteristics of the watershed surface on the accumulative surface runoff curve.

Laws may be developed from such an approach which may be applicable anywhere, although certain factors may vary in magnitude based on the soil and climatic province under consideration. This paper attempts to set up relationships between soil-water movements and surface runoff that can be applied to other soils. However, it would be necessary to determine certain hydrologic characteristics of other soils as was done for the soils mentioned herein. Since the approach in this paper is believed to be a fundamental one it does not preclude soils which tend to seal or crack. Velocity or transmission rates through such soils may also be approximated and such rates may be related to the pore space or crevices and cracks through which major movements of water downward occur. Seasonal differences in the hydrologic characteristics of soils may also be accounted for in this approach as consideration may be given to seasonal changes in soil-water movements.

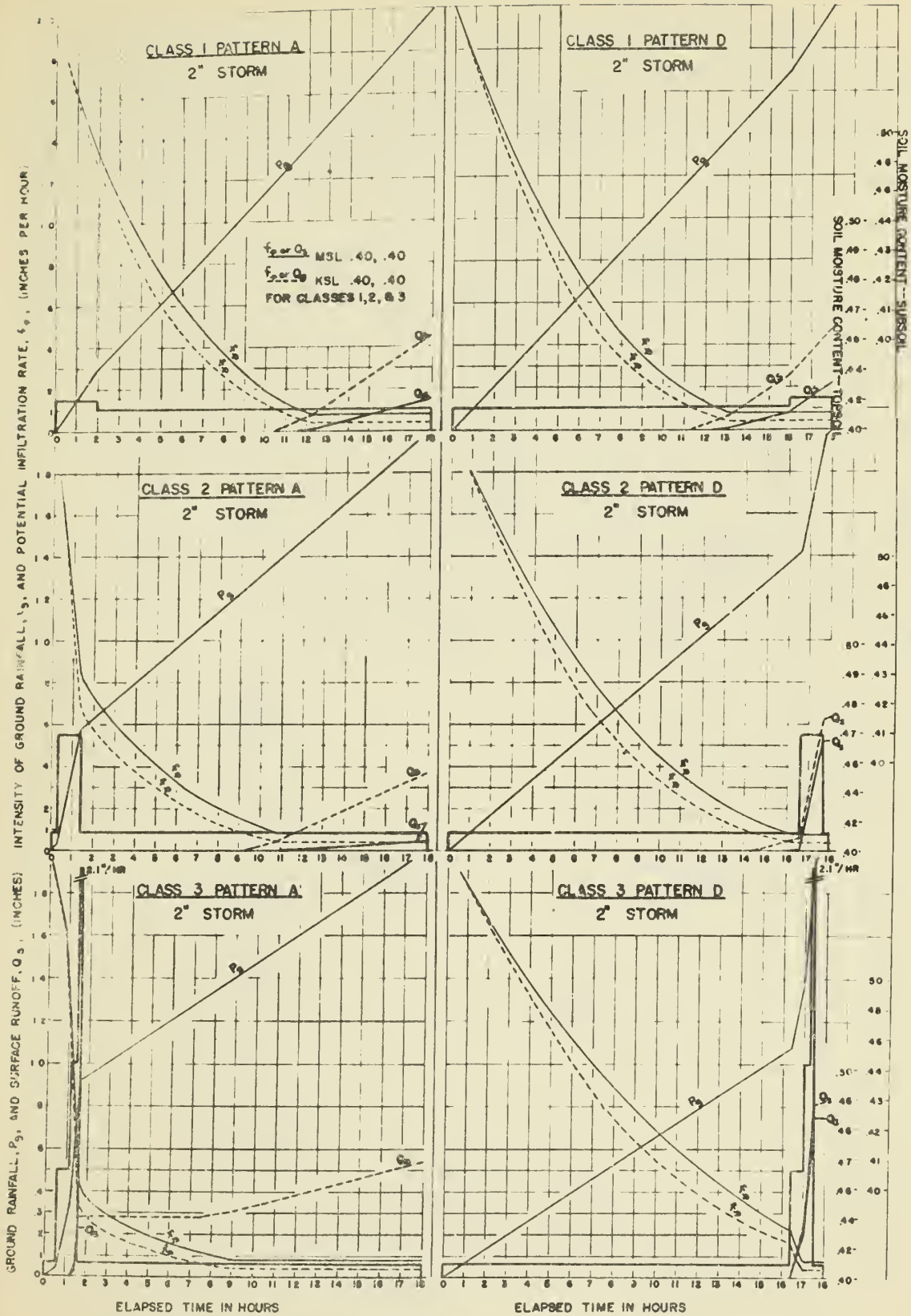
CLASS 1 PATTERN A
2" STORM
CLASS 1 PATTERN D
2" STORM
f_p or Q_s M3L .40, .40
f_p or Q_s K5L .40, .40
FOR CLASSES 1, 2, & 3
CLASS 2 PATTERN A
2" STORM
CLASS 2 PATTERN D
2" STORM
CLASS 3 PATTERN A
2" STORM
CLASS 3 PATTERN D
2" STORM
2.1"/HR
2.1"/HR
INTENSITY OF GROUND RAINFALL, i_g, AND POTENTIAL INFILTRATION RATE, f_p, (INCHES PER HOUR)
GROUND RAINFALL, P_g, AND SURFACE RUNOFF, Q_s, (INCHES)
SOIL MOISTURE CONTENT--SUBSOIL
SOIL MOISTURE CONTENT--TOPSOIL
SOIL MOISTURE (INCHES WATER PER INCH SOIL)
ELAPSED TIME IN HOURS
ELAPSED TIME IN HOURS

FIG. 5 - SURFACE RUNOFF ESTIMATES BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERNS

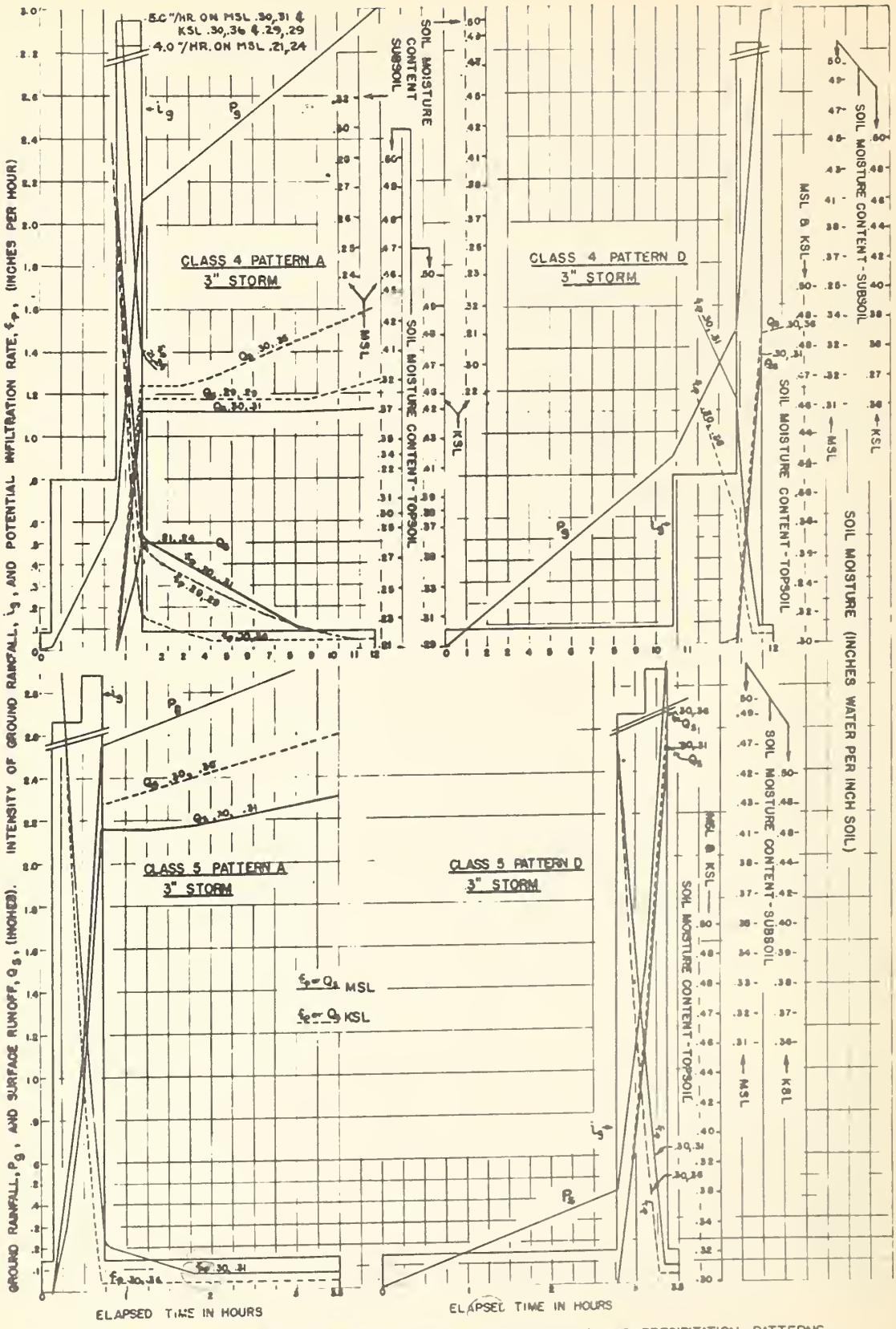
5.0 "/HR ON MSL .30,.31 &
KSL .30,.36 & .29,.29
4.0 "/HR. ON MSL .21,.24
CLASS 4 PATTERN A
3" STORM
CLASS 4 PATTERN D
3" STORM
CLASS 5 PATTERN A
3" STORM
CLASS 5 PATTERN D
3" STORM
MSL
KSL
SOIL MOISTURE CONTENT-SUBSOIL
SOIL MOISTURE CONTENT-TOPSOIL
SOIL MOISTURE (INCHES WATER PER INCH SOIL)
GROUND RAINFALL, P_g, AND SURFACE RUNOFF, Q_s, (INCHES). INTENSITY OF GROUND RAINFALL, i_g, AND POTENTIAL INFILTRATION RATE, f_p, (INCHES PER HOUR)
ELAPSED TIME IN HOURS
ELAPSED TIME IN HOURS

FIG. 6 - SURFACE RUNOFF ESTIMATES BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERNS.

It would seem desirable to determine the hydrologic characteristics of major soils of the country that show important differences in permeability. These soils could then be grouped hydrologically. Soils for which such determinations were not practical could probably be fitted reasonably well into the established groups. Such a grouping related to a grouping of climatic provinces would be a powerful tool in evaluating land-use practices and in problems involving runoff.

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